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Final Engineering Report

of the

AUDIO SPECTRUM ANALYZER MRFR 30-3

23 March 1956

Raytheon Manufacturing Company
Sonar Department, Wayland Laboratory
Wayland, Massachusetts

Contract No. Nonr-1368(00)

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ABSTRACT

Details are given of the performance of an Audio Spectrum Analyzer developed by the Raytheon Manufacturing Company under Contract Nonr 1368(00). Operating between 40 and 4200 cycles per second, the Analyzer uses 420 magnetostrictive rod filters whose bandwidths are approximately 10 cycles at the 3-db down point. These filters are driven simultaneously and continuously by the exciting signal. The filter center frequencies are 10 cycles apart, and the outputs are scanned by a capacitive commutator and displayed on a separate oscilloscope. This report covers the frequency definition, frequency resolution, frequency response, dynamic response, and signal-to-noise characteristics of the Analyzer.

Recommendations for future work include improvement of the individual filters used in the Analyzer so that a more uniform frequency response may be obtained, and improvements and changes in the output amplifier to extend the utility of the instrument.

Results indicate that an instrument of this type is useful in conjunction with active and passive sonar systems to interpret and/or supplement target information such as target doppler, range rate, frequency distribution of signals in the presence of a noise background, and measurement of relative amplitudes of various input signals.

FINAL REPORT OF THE OPERATING CHARACTERISTICS OF THE AUDIO SPECTRUM ANALYZER MRFR 30-3

SCOPE: The work covered by this report includes the following sections:

FINAL REPORT OF THE OPERATING CHARACTERISTICS OF THE AUDIO SPECTRUM ANALYZER MRFR 30-3

1. OBJECT

The object of this report is to relate the pertinent operating characteristics of the Audio Spectrum Analyzer MRFR 30-3 designed and developed by the Raytheon Manufacturing Company.

2. INTRODUCTION

The Audio Spectrum Analyzer consists of 420 magnetostrictive rod filters whose bandwidths are approximately 10 cps at the half-power point and whose center frequencies are approximately one bandwidth apart. The audio spectrum to be analyzed is translated by a local oscillator to the frequency range covered by the magnetostrictive rod filters. In the case of the MRFR 30-3, these frequencies fall roughly between 83.2 and 87.4 kc, at which frequencies the required Q's are approximately:

$$Q = \frac{f}{\Delta f}$$

$$Q = \frac{85 \times 10^3}{10} = 8500,$$

where f = center frequency

Δf = bandwidth at half-power point.

Q's of this order are obtainable by using magnetostrictive rod filters whose Q's range between 4000 and 10,000 in a frequency band between 10 kc and 500 kc[1]. The rod filters are driven simultaneously in a series-parallel arrangement, and the output of each filter is connected to a plate on a capacitive commutator. Out-of-phase summation of adjacent filters is used to provide sharp skirt responses and high resolution. The AC signal from the commutator then is amplified, detected and fed through a cathode follower to the output terminals, where the signal is available for use by a standard scope. A sync coil mounted on the commutator provides an indexing signal for each revolution of the commutator to insure synchronizing of the sweep on the oscilloscope with the audio spectrum under investigation.

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[1] High-Speed, High Resolution Spectrum Analyzer - Nesbit L. Duncan, Raytheon Manufacturing Company, Missile and Radar Division, presented at 1954 IRE Convention.

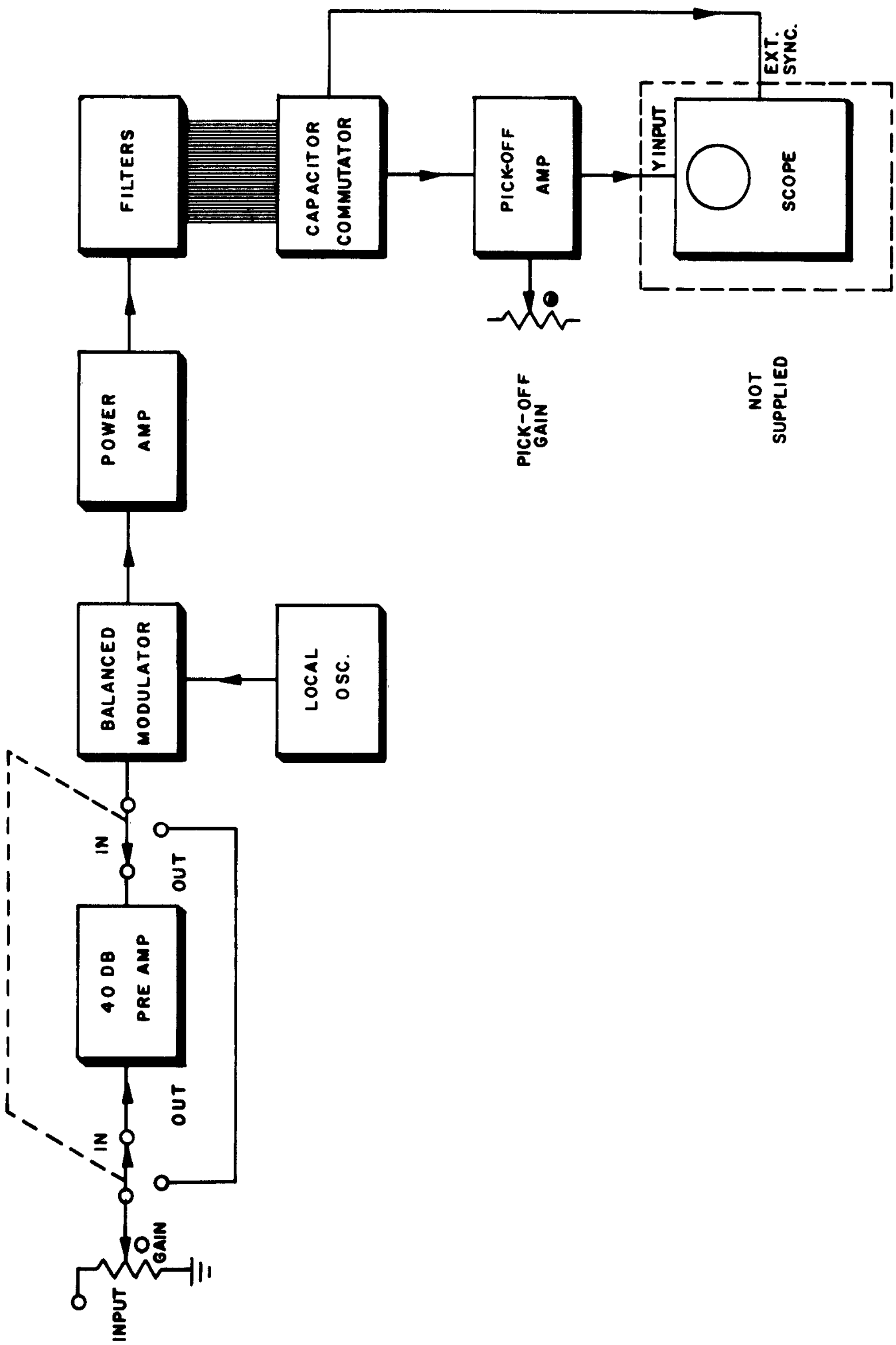

FILTERS
CAPACITOR COMMUTATOR
PICK-OFF AMP
Y INPUT
SCOPE
EXT. SYNC.
POWER AMP
BALANCED MODULATOR
LOCAL OSC.
40 DB PRE AMP
IN
OUT
IN
OUT
INPUT
GAIN
PICK-OFF GAIN
NOT SUPPLIED

Figure 1.

3. CONSTRUCTION OF THE ANALYZER

Figure 1 shows a circuit block diagram of the Analyzer. The rod filters are driven in the following arrangement: the 20 filters comprising one panel have their drive coils connected in series. Three of the panels (BK-1 to BK-3) then are connected in series, giving 60 rods in series. The remaining 360 rods are connected in the same manner, giving a total of 7 groups of 60 rods. These 7 groups then are connected in parallel and driven by the power amplifier so that all filters are driven simultaneously and continuously by the exciting signal. Since the impedance per filter is approximately 20 ohms, the over-all impedance of the filter is approximately 170 ohms at the operating frequency.

The action of the rod filters is as follows: the electrical signal in the drive coil creates a magnetic field which causes the magnetostrictive rod to vibrate. When the vibration is at the natural resonant frequency of the rod, the mechanical motion of the rod is maximum. The vibration of the rod is reconverted into an electrical signal by magnetostrictive action at the pickup coil. Vibrations which are not at the resonant frequency of the rod are highly attenuated in the rod and no motion is present at the pickup coil to be converted into an electrical signal. The electrical signal in the pick-off coil then is fed directly to a plate on the capacitive commutator.

Figure 2 shows how a group of 20 rod filters are assembled, and Figure 3 shows how 21 individual groups of 20 are arranged around the commutator.

The local oscillator in the Analyzer uses a tuned circuit consisting of a magnetostrictive rod assembly similar to the rods used in the filter section. This is a compensating feature so that, if the center frequencies of the rod filters tend to change due to temperature rise, the local oscillator frequency will shift correspondingly and the commutated output will not shift its calibration as the system warms up.

If it is desired to use the Analyzer for frequency bands other than the 40 to 4200 cycles for which the MRFR 30-3 is basically intended, an external frequency source may be inserted in place of the local oscillator so that the band can be shifted to the region of interest. If this is done, retuning the balanced modulator may be required. Attention should be paid to the possibility of undesired image responses if the Analyzer is to be used in this manner.

4. FREQUENCY DEFINITION

Figure 4 is a photograph of an oscilloscope presentation in which the Analyzer is used to determine the frequency of a single unknown signal. The horizontal sweep of the oscilloscope is synchronized with the analyzer sync pulse, and the oscilloscope is calibrated so that the unknown frequency may be determined by interpolation. In Figure 4a, the calibration marks are at 1000, 2000, 3000, and 4000 cycles, and the "unknown" signal is 1700 cycles. In Figure 4b the "unknown" signal is 2600 cycles.

A distinct advantage to this Analyzer is that the frequency scale used is linear along the frequency axis for any display. This makes it possible to obtain the same frequency-resolving characteristic over any portion of the frequency scale, and thus, the accuracy of interpolation is identical for all frequencies. The limitation to the accuracy of this method is the calibration of the oscilloscope and the linearity of the horizontal sweep as far as interpolation on the scope is concerned. Figure 5a is a multiple exposure of a group of output pulses. The 3 peaks

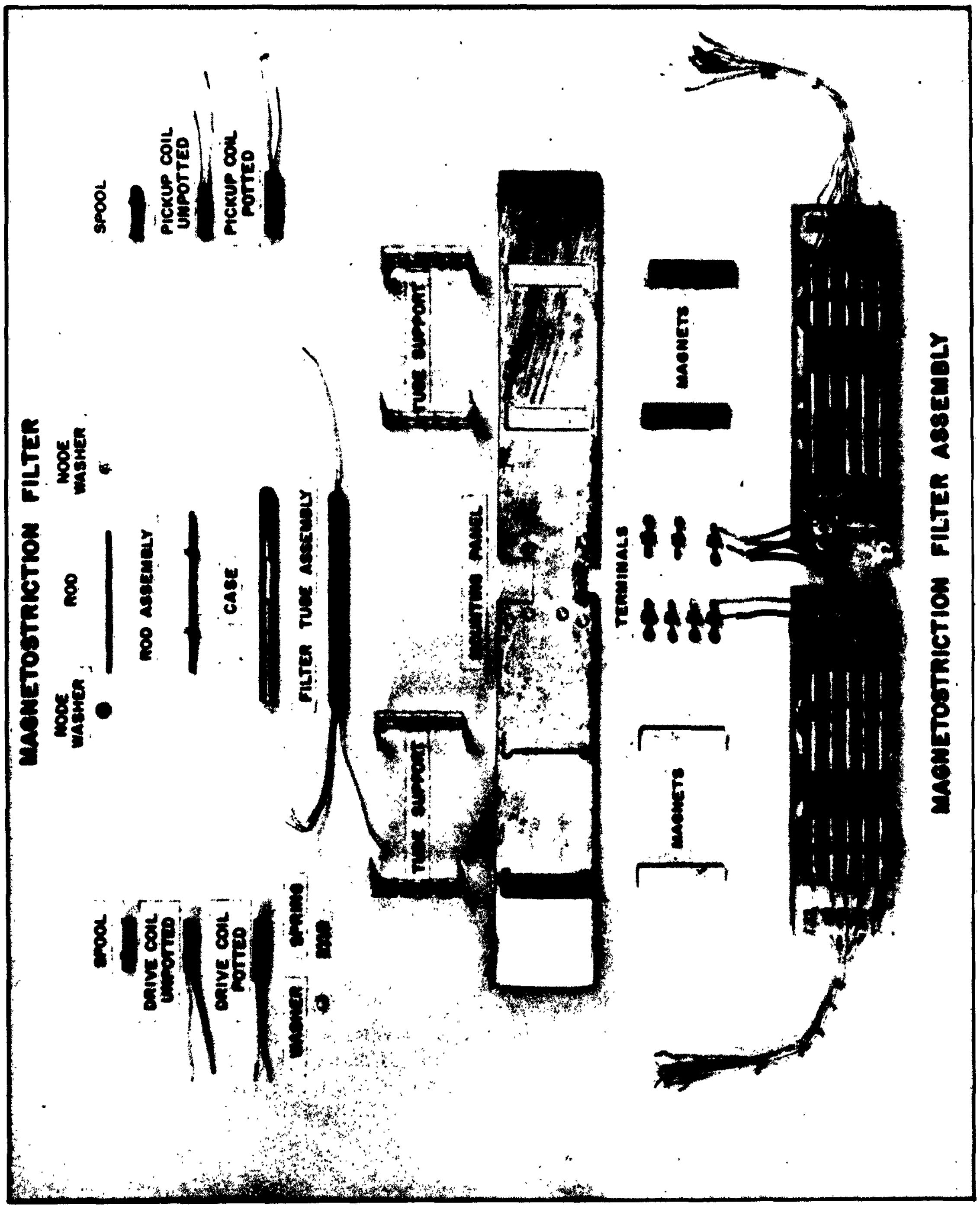

MAGNETOSTRICTION FILTER
NODE WASHER
ROD
NODE WASHER
ROD ASSEMBLY
CASE
FILTER TUBE ASSEMBLY
SPOOL
PICKUP COIL UNPOTTED
PICKUP COIL POTTED
TUBE SUPPORT
TUBE SUPPORT
TERMINALS
MAGNETS
MAGNETS
SPOOL
DRIVE COIL UNPOTTED
DRIVE COIL POTTED
WASHER
SPRING
MAGNETOSTRICTION FILTER ASSEMBLY

Figure 2.

are approximately 10 cycles apart. Figure 5b is a single time exposure taken to show that there are definitely 4 peaks (as the input frequency was swept back and forth over a 40-cycle increment). The center frequency is 300 cps in this case.

In conjunction with the frequency-definition measurements, the base width of the output pulse was measured. This is shown in Figure 6a. Figure 6b is a calibration signal of 3800 cycles per second. The pulse width is approximately one period of the 3800-cycle signal which is equal to 264 microseconds. The horizontal sweep of the oscilloscope has been expanded in this case. The base widths of all the pulses over the frequency range are of this order of magnitude.

A somewhat more accurate and easier way to determine the frequency of a steady-state signal is to mix with the unknown signal the output of a calibrated frequency source and to vary the frequency of the known source until the two signals beat together in the heterodyne mixer. As the frequency is approached, a beat will be noticed between the two pulses. By careful adjustment a zero beat can be obtained in which the pulses on the oscilloscope blend into one and slowly oscillates up and down as the two signals gradually come in and out of phase. The advantage of this method of determining frequency is that it is possible at all times to see whether the unknown frequency is higher or lower than the known frequency.

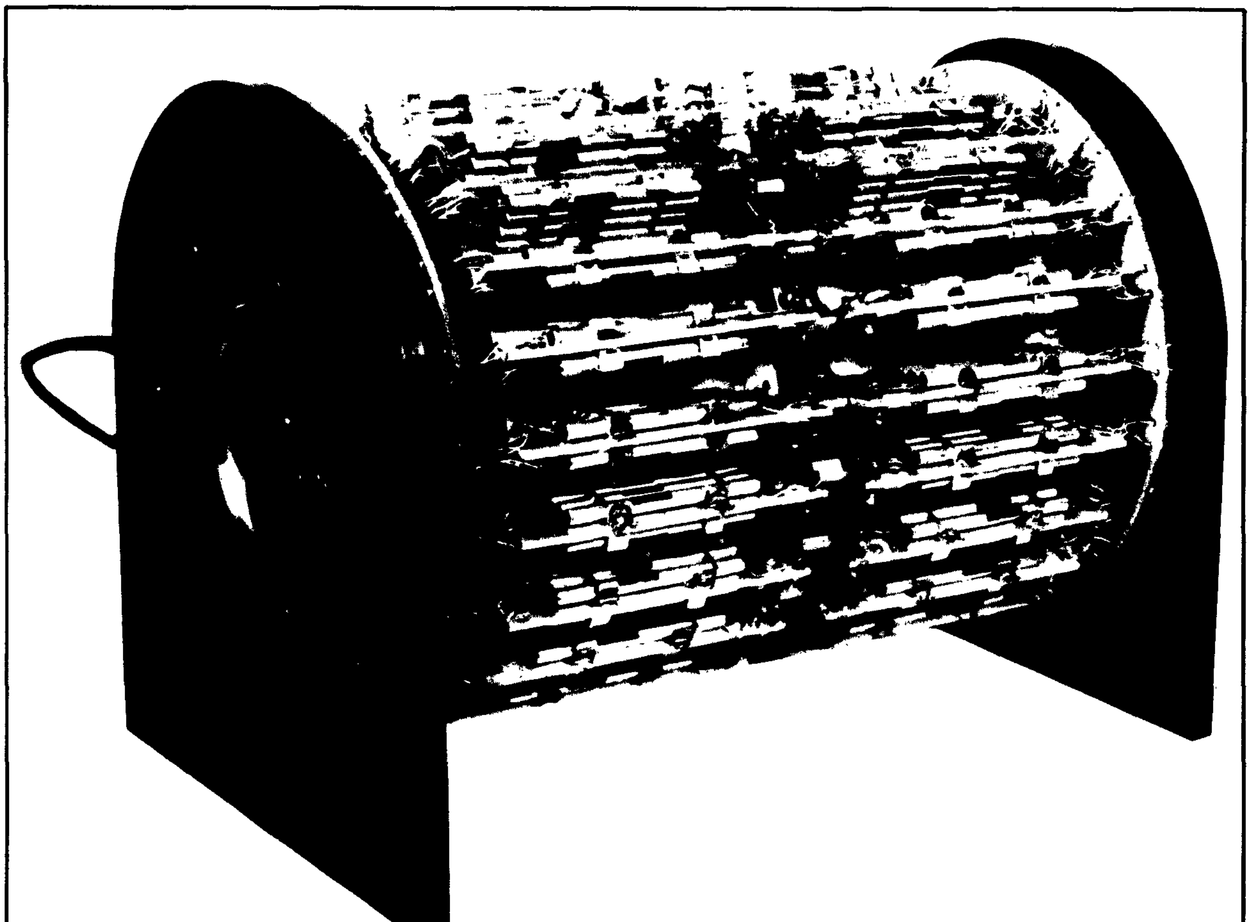


Figure 3.

a.

b.

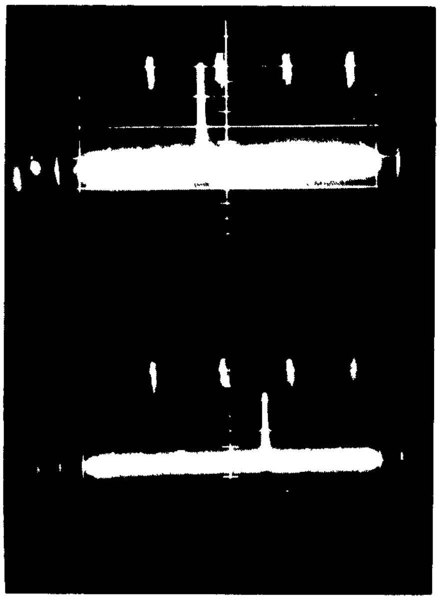


Figure 4.

a.

b.

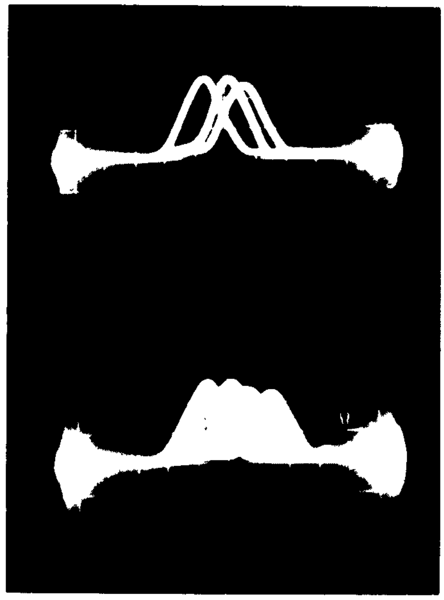


Figure 5.

a.

b.

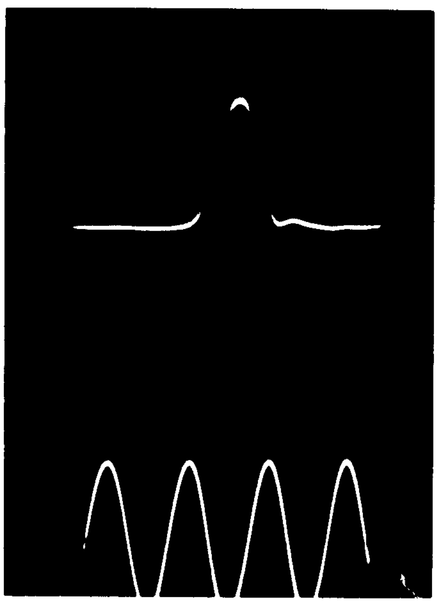


Figure 6.

a.

b.

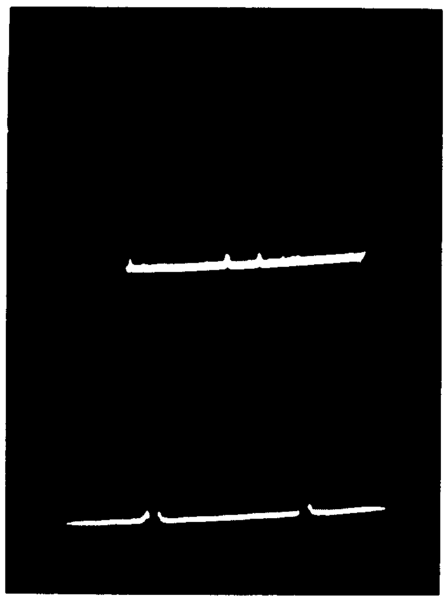
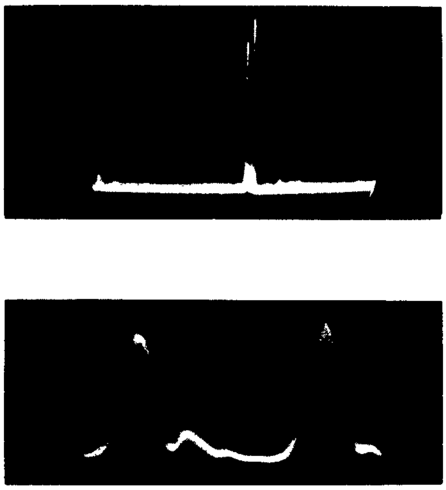


Figure 7.



a.

b.

Figure 8.

a.

b.

Figure 9.

5. FREQUENCY RESOLUTION

Figure 7 shows two frequencies being fed simultaneously into the Analyzer at 1500 and 2000 cycles. Figure 7a shows the two frequencies as presented on a normal oscilloscope presentation, and in Figure 7b the horizontal sweep has been expanded to show the resolving characteristics of the Analyzer at these input frequencies. Figure 8 is a photograph of two frequencies 90 cycles apart, namely, 1910 and 2000 cycles. Figure 8a is the normal presentation, and Figure 8b is an expanded view of 8a, showing the definite distinction between the two frequencies. Figure 9a shows two signals of 30 cycles difference, and 9b, two figures of 10 cycles difference on an expanded basis only. In Figure 9b, the two signals are beginning to beat together as explained above under the section on Frequency Definition. In conjunction with the frequency resolution, another type of display was used for demonstration. The horizontal sweep was driven as before and synchronized with sync pulse from the Analyzer. A low-frequency sawtooth voltage was used for vertical deflection, and the pulses from the Analyzer were introduced into the Z axis of the oscilloscope. Figure 10 shows 1500 and 2000 cycles with a normal and expanded presentation; Figure 11 shows 1900- and 2000-cycle signals normal and expanded; Figure 12a shows two signals 20 cycles apart, and 12b, ten cycles apart on an expanded basis only.

6. FREQUENCY RESPONSE

In order to measure the over-all frequency response of the Audio Spectrum Analyzer, a Leeds and Northrup Speedomax Recorder was used. A diode detector was used to convert the output pulse from the Analyzer, which occurs approximately at 30 cps, to a sawtooth waveform whose AC components were used to drive the Speedomax Recorder via a McIntosh Amplifier. The recorder was driven at a continuous speed as was the oscillator whose signal was fed to a.

b.

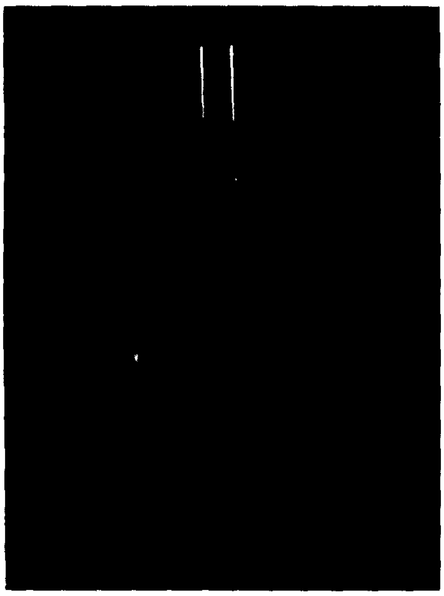


Figure 10.

a.

b.

Figure 11.

a.

b.

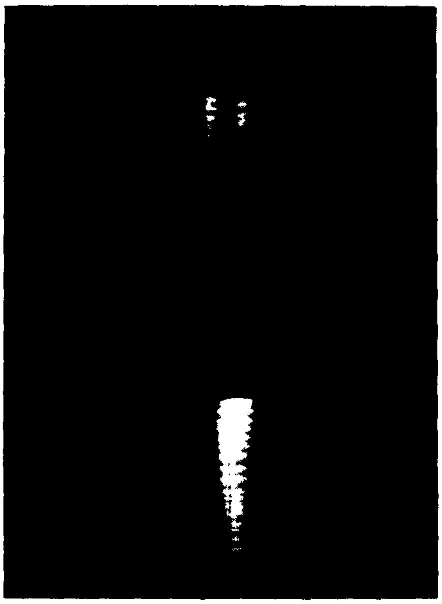


Figure 12.

the Analyzer. The input frequency did not vary linearly with time—therefore, the need for the special calibration in Figures 13, 14, and 15. In Figure 13 the input to the Analyzer was 1 volt (0 db), in Figure 14 the input was 0.57 volt (-5 db), and in Figure 15 the input was 0.32 volt (-10 db). From these curves the frequency response of the recorder can be seen to be very erratic through the spectrum over which the Analyzer was designed to operate. Two things are apparent from the curves: the first and most obvious is that the responses of the filters are not uniform over the frequency range; and the second is that the output of the Analyzer does not vary directly with the input.

The variation in output over the spectrum is fundamentally due to two things: (1) The variation in insertion loss and Q of the rod filters, and (2) the drift of the center frequency of one filter relative to adjacent filters. This is known as "interlacing" and can cause a "hole" or "peak" at that frequency. An example of this is shown at X (at approximately 1320 cycles per second) on Figure 15. The cause of the irregularities in the swept-frequency response is given in the following paragraph.

The major problem incurred during manufacture of the Analyzer was the stability of the magnetostrictive rod filters. Prior to the manufacture of this Analyzer, Raytheon had built a similar Analyzer using 25-cps filters with good results. When the 10-cps filters were contemplated, it was felt that the manufacture of these filters would be a straightforward extrapolation from the results of the 25-cps filters previously built. However, this assumption did not hold true, due to the tightened tolerances required.

After the rod filters were manufactured for the equipment, they were stored for one month to determine their stability. A recheck of the filters showed variations in both output voltage response and bandwidth measurements. The cause of these discrepancies were found to be:

a. Misalignment of rods and filter cases (ratio of case length to wall thickness was too large).

b. Shift in potting compounds after curing.

c. Incorrect staking procedure (node washers to rod).

d. Foreign matter in filter cases and on rods (insufficient quality control).

The predominate trouble makers were found to be warped filter cases and loose node washers. In order to eliminate or minimize these causes of filter failure, a redesign of the filter was necessary. This redesign has been incorporated into later Raytheon Spectrum Analyzers.

Due to the narrow bandwidth and high Q's required, any differential drift of the filters in frequency or insertion loss due to temperature variations or other causes can show up in the over-all frequency response as a "hole" in the spectrum. This "hole" occurs when "interlacing" takes place, in which one of a group of filters drifts more or less than the others. It has been found that, when the filters are correctly spaced with crossover points at or near the half-power points, the output response of the Analyzer should have a theoretical peak variation of 1.6 db. If the outputs of the filters are within ± 0.5 db and the bandwidth and frequency-separation deviations are as large as 10% of the filter element bandwidths, the output of the Analyzer has a 3- or 4-db variation. When rod output variations exceed ± 3 db or the frequency shift exceeds 20% of the filter element bandwidths, the depth of the hole exceeds 6 db. In the case where the resonant frequencies of two filters occur at the same frequency, variations in the Analyzer output may be as great as 10 db below the average.

This shows some of the problems encountered in attempting to make the Analyzer useful for quantitative measurements. To supplement the swept-frequency response, photographs (Figure 16) were taken. These two multiple-exposure photographs show the response of the Analyzer for a fixed voltage input over the frequency spectrum of the instrument. Figure 16a is a 0.35-volt input at 100-cycle increments, and Figure 16b is a 1-volt input at 200-cycle increments. The gain of the scope was set accordingly, so a good deflection of the vertical sweep resulted. The object of these photographs is to show that the variation of output is not a continuously variable function; instead, a group of filters may be fairly uniform except for one or two whose response may be high or low in amplitude. Apparent also in these photographs is the square-law response of the Analyzer, which is particularly noticeable at low input levels as described in the following section.

7. DYNAMIC RESPONSE

As can be seen by an examination of Figures 13, 14, and 15, a total of 10 db of variation in the input causes 20.5-db variation in the output at a frequency of approximately 1400 cycles and 18-db variation at 2300 cycles. Thus, it can be seen that, for a 10-db change in input at the level chosen, approximately a 20-db change in output results. This can be substantiated further by referring to Figure 17, which is a plot of signal output vs input. Two curves are shown: the Analyzer Response Curve is the over-all response of the Analyzer, and the Drive Amplifier is the input vs the output of the power amplifier which feeds the commutator. It is apparent that there is a square-law action present which accounts for the nonlinear dynamic response of the swept-frequency response curves. This square-law action is a result of running the diode detector used as an envelope detector at too low a signal level.

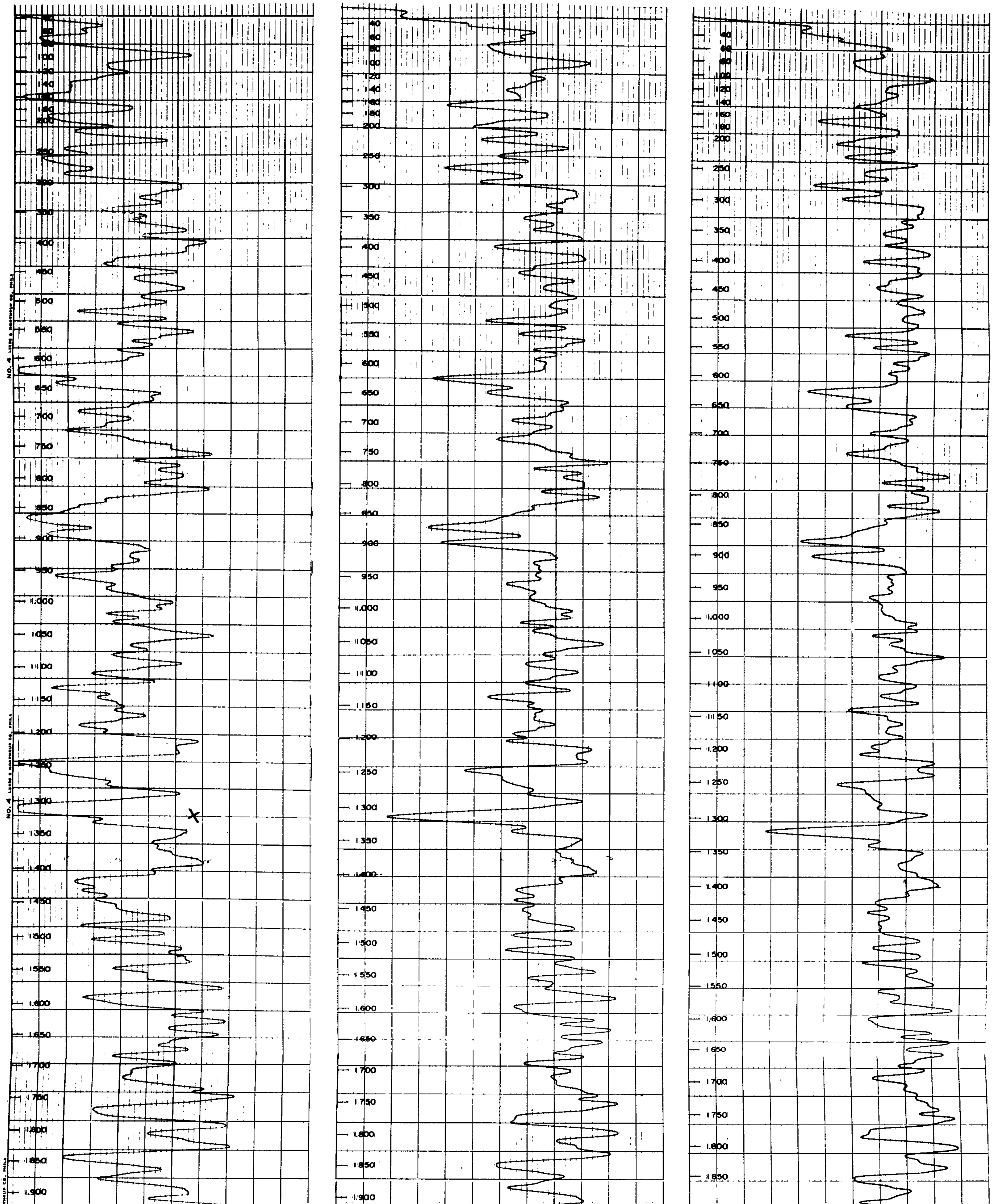
Figure 18 again shows the dynamic response of the Analyzer with a single input frequency. This is similar to that shown in Figure 17, except the input was increased until saturation resulted. From these two curves it can be seen that there is a range of only about 10 db over which the output is essentially linear, and this occurs for signals between 0.3- and 1-volt input for the preamplifier out and all other gains maximum at the input frequency chosen. If the signal level were increased at the detector so that the detector operated in its linear range, then the square-law action would be less noticeable.

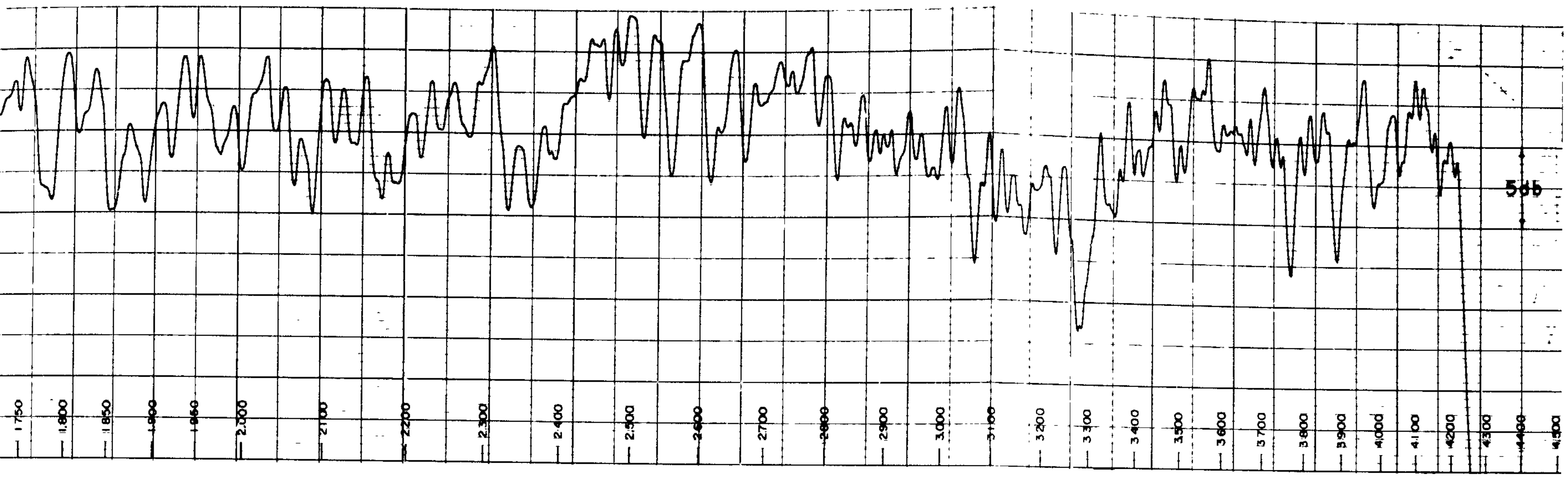
8. SIGNAL-TO-NOISE MEASUREMENTS

With the Analyzer gain at full, the preamplifier on, and the pick-off gain (internal adjustment) fully counterclockwise, a 0.1-millivolt signal can be seen in the Analyzer noise as the frequency is changed across the range of the Spectrum Analyzer. In order to be certain that a frequency is present at this input level, it is necessary to change the frequency so the output pulse will move through the noise. A higher signal level of at least 0.15 millivolt is necessary so that the signal pulse can be readily discriminated from the noise for a static input frequency. These measurements were made with an audio frequency inserted into the Analyzer through an Audio Frequency Microvolter GR Type 546B.

9. PRACTICAL USE OF THE ANALYZER

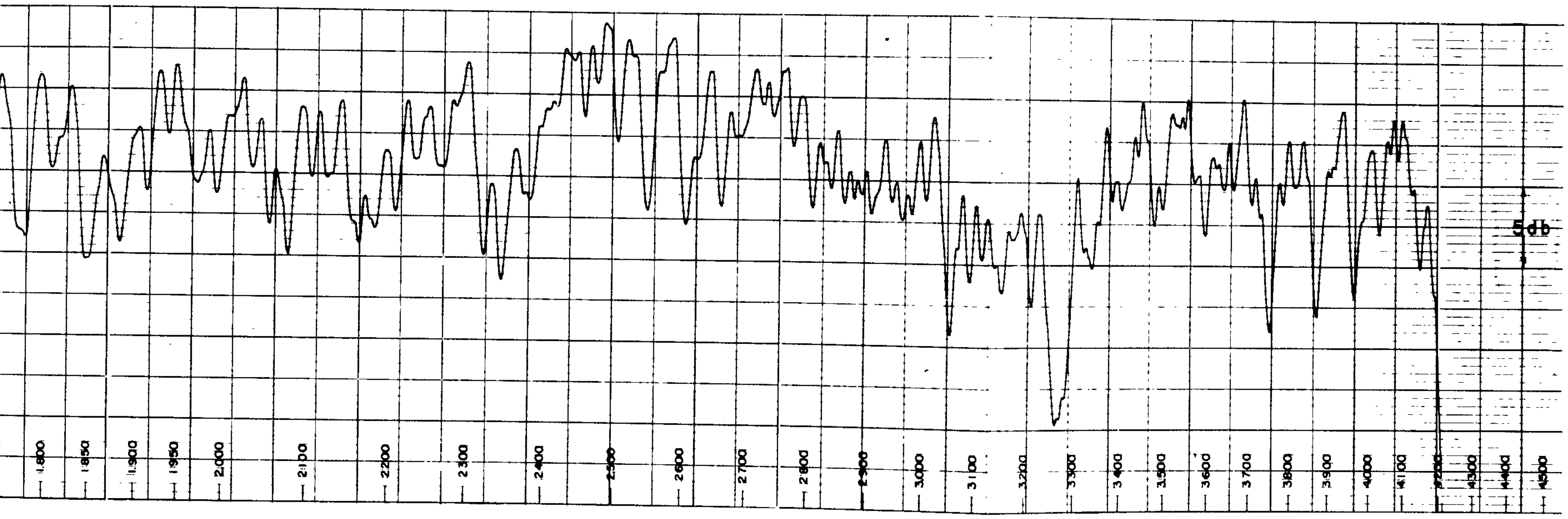
A block diagram of the circuit used to study the practical use of the Analyzer under realistic conditions is given in Figure 19. The calibration oscillator was used to determine the frequency of a given signal component from the recordings on the tape recorder. The Ballantine amplifier was used to amplify the output of the Analyzer to a level adequate to brighten the oscilloscope. The amplifier and phase inverter were required to obtain the correct polarity of the Analyzer pulse for the oscilloscope brightening. A long persistence screen was used.





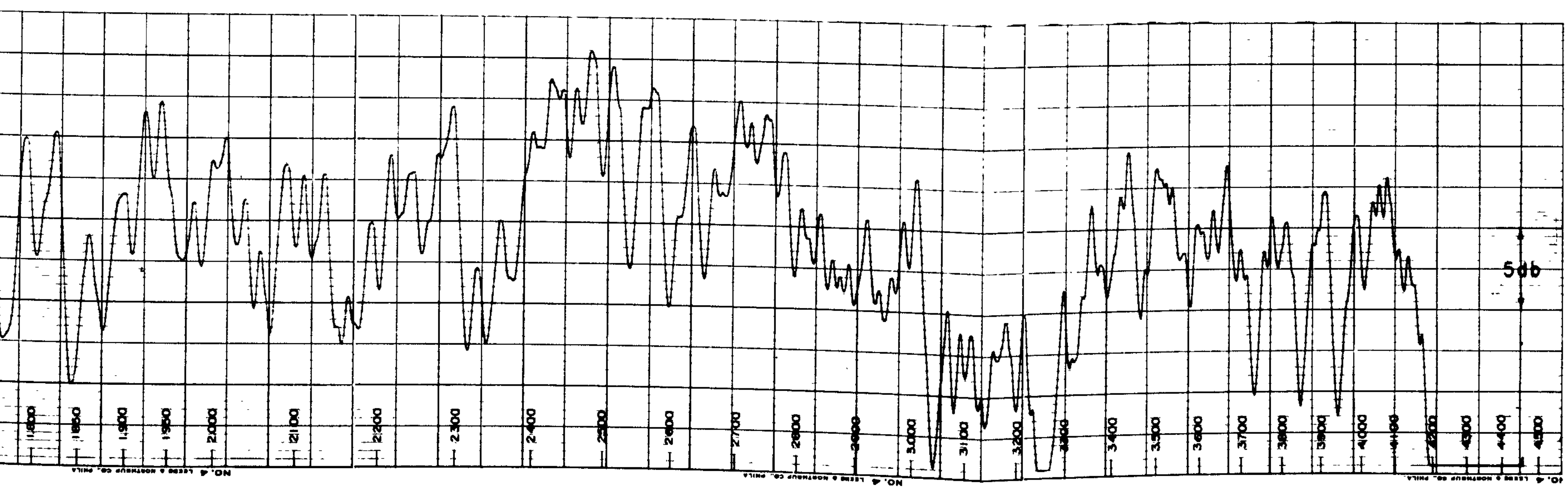
AUDIO SPECTRUM ANALYZER MRFR 30-3
SWEPT - FREQUENCY RESPONSE
INPUT 0 db (1 VOLT)

Figure 13.



AUDIO SPECTRUM ANALYZER MRFR 30-3
SWEPT - FREQUENCY RESPONSE
INPUT - 5 db

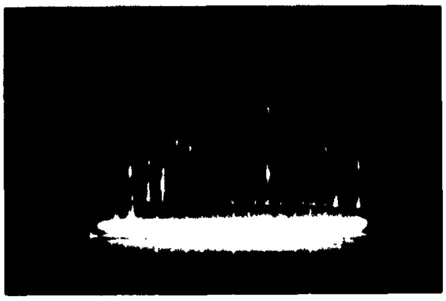
Figure 14.



AUDIO SPECTRUM ANALYZER MRFR 30-3
SWEPT - FREQUENCY RESPONSE
INPUT - 10 db

Figure 15.

a.



b.

Figure 16.

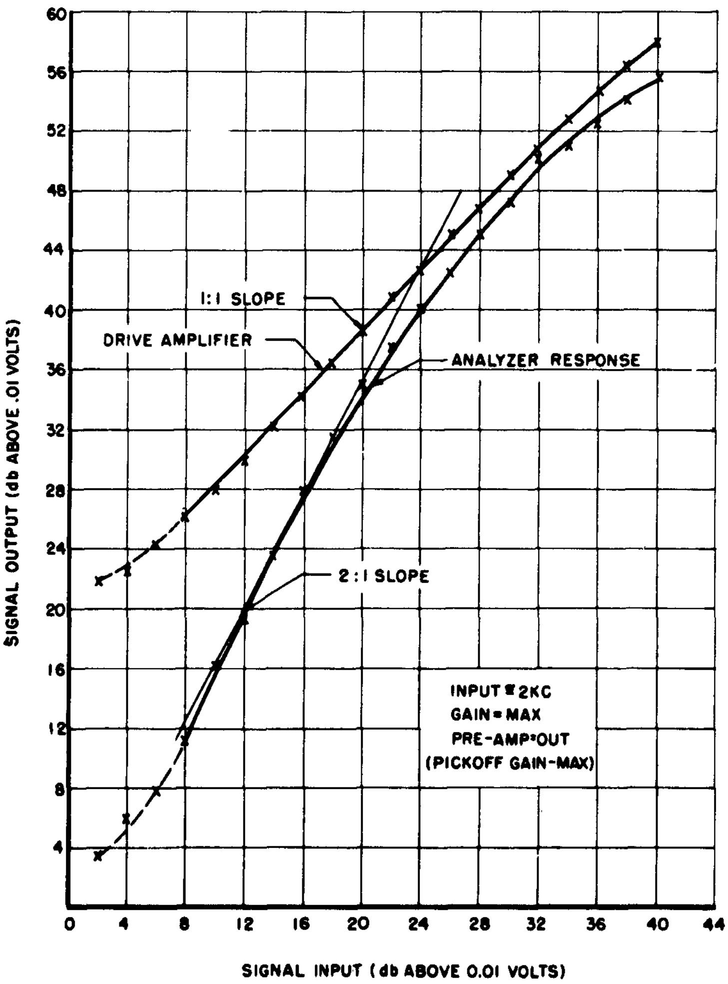


Figure 17.

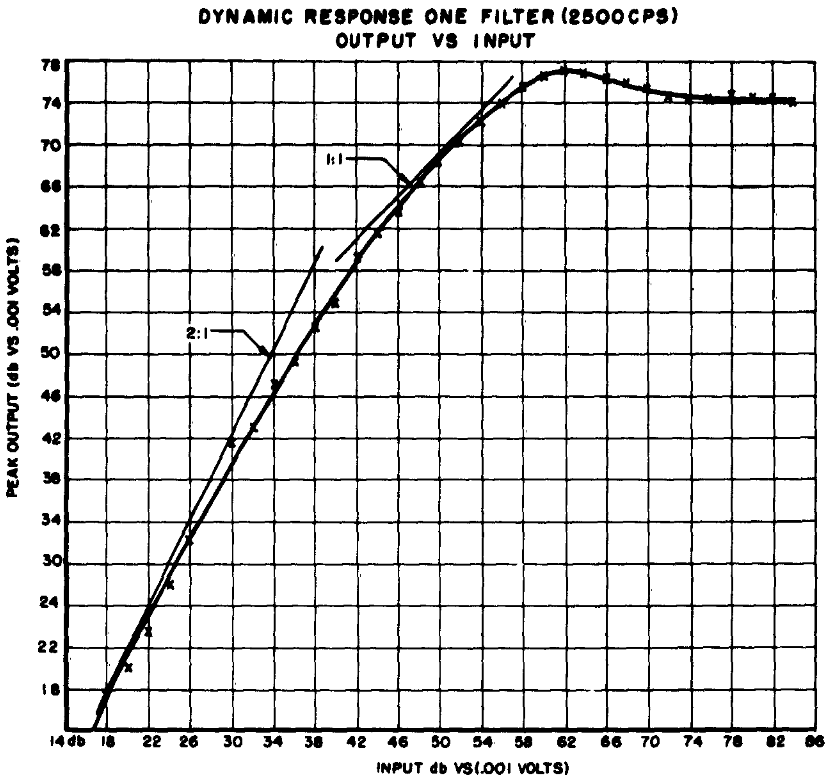


Figure 18.

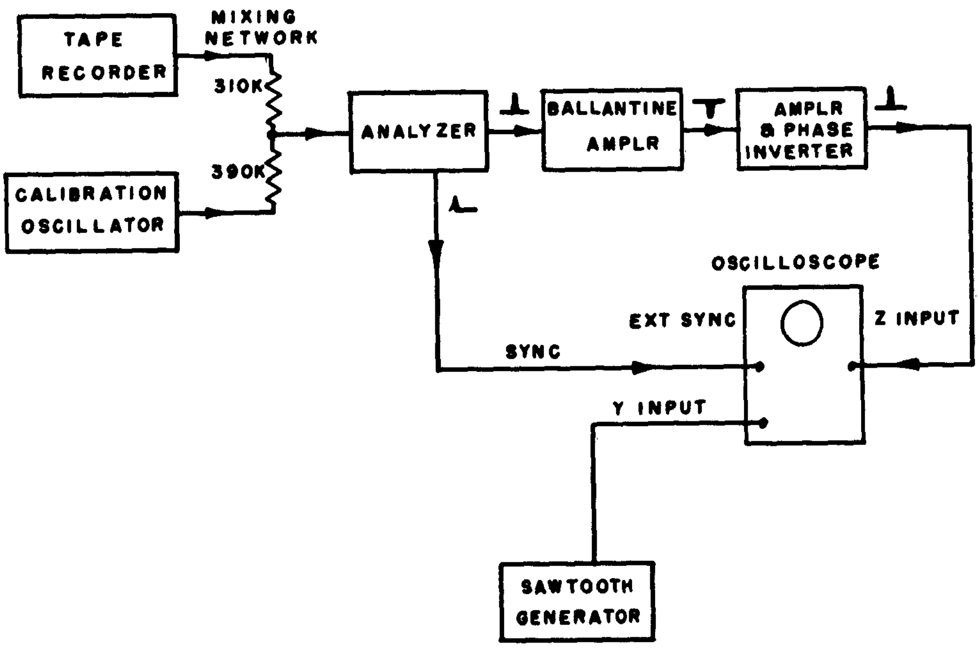


Figure 19.

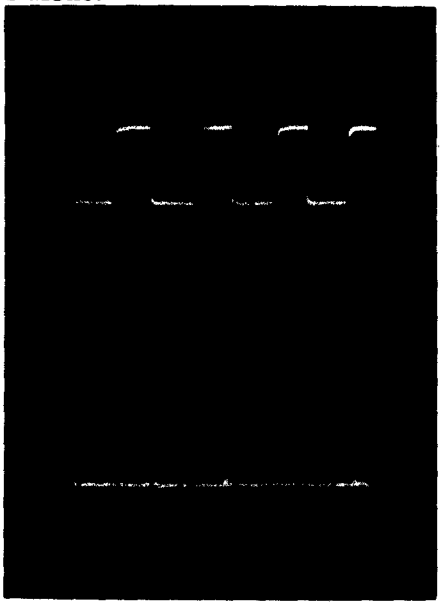
Block Diagram of Circuit Used to Study Characteristics of Analyzer

The display, as seen on the oscilloscope, had frequency on the horizontal axis, time on the vertical axis, and amplitude on the Z axis. The advantage of such a display is that, provided the oscilloscope has a long enough persistence, a frequency change over a long period of time can be noticed readily. If the sawtooth generator is synchronized with the keying pulse of a sonar transmitter, then, from such a display, the range and range rate of a target can be observed by an operator by proper calibration of the oscilloscope. If the operator so desires, he can expand the frequency scale on the horizontal axis so that the frequency range of particular interest to him covers the entire face of the oscilloscope. With this type of display the amplitude variations from the Analyzer are not as disturbing as they were when using the straight frequency-amplitude display. If need be, the pulses from the Analyzer may be limited and differentiated in order to limit "blooming" of the oscilloscope for large amplitude inputs to the Z axis. The only photographs available of this type of display are Figures 10, 11, and 12. Pictures of actual sonar recordings were not possible with the equipment available.

The Analyzer is also useful for the analysis of complex waveforms to determine their harmonic content. Figure 20a shows the harmonic content of a 1000-cycle rectangular wave; Figure 20b indicates that there are frequency components present at 1000, 2000, 3000, and 4000 cycles per second. Figure 21 is an analysis of the harmonic content of a 1000-cycle sawtooth with harmonic present at 1000, 2000, 3000, and 4000 cycles per second. The relative magnitudes of the Analyzer output pulses are not too meaningful, due to the poor frequency response of the Analyzer as described in Section 5.

10. RECOMMENDATIONS FOR FUTURE WORK

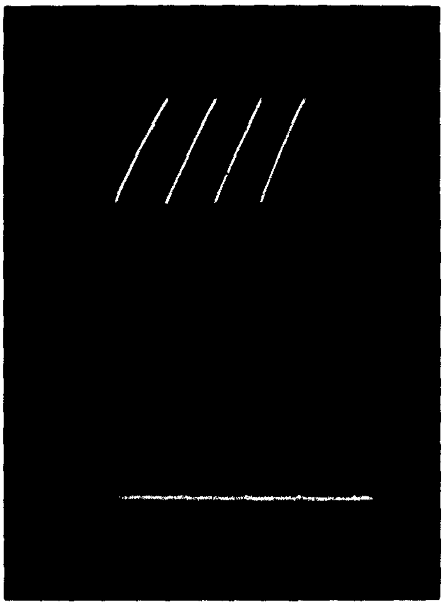
From a study of the swept-frequency response, it can be seen that the variation in output pulse height as a function of input frequency is the major problem so far encountered in using the Analyzer. The Raytheon Mfg. Co., since the manufacture of this instrument, has investigated the characteristics of the individual filters in an attempt to determine and understand more fully the phenomena associated with magnetostrictive rod filter design. Future work would encompass a more detailed understanding of the production problems so that a better quality control can be maintained and more reliable filter produced. During the manufacture of this model, the rejection rate was approximately 80% on the magnetostrictive rod filters alone.



a.

b.

Figure 20.



a.

b.

Figure 21.

The other major improvement necessary for this instrument is in the dynamic response characteristics of the Analyzer. The square-law action can be eliminated by running the diode detector on a more nearly linear portion of its characteristics. The latter improvement can be accomplished by means of a redesign of the pick-off amplifier circuit.

In measuring the signal-to-noise ratio of the Analyzer, it was observed that the major hinderance to the observation of small signals was a 120-cycle ripple present in the output. Because the commutator does not run at synchronous speed, there is relative motion between the synchronized Analyzer output and the ripple voltage. The observation of very small signals would be facilitated by substituting a synchronous motor for the induction motor used in the present model. Better filtering of the supply voltage is not the only answer, since, if any ripple is present, any relative motion on the oscillographic presentation can be objectionable.

Assuming that the response of the rod filter can be made uniform, a worthwhile improvement would be to add a logarithmic amplifier so that the amplitude characteristics can be either linearly related to the frequency components of the input or to the logarithm of the input.

If an approach similar to that used with this equipment is to be used in an active sonar system, then the filters and associated commutator could be designed to operate only over the frequency range in which doppler might be expected on the returning echo. The intermediate frequency of the sonar receiver could be chosen to be within operating frequency range of the filters (approximately 85 kc with this model) and would prove to be a definite asset to an operator in determining doppler, particularly at the low-frequency systems now in use. For a 10-kc signal, the doppler is approximately 7 cycles per knot of range rate, and at 5 kc, only about 3.5 cycles per knot of range rate. Providing that the filter could be made with an even higher Q, a valuable contribution to the sonar attack problem could be made by simplifying the instantaneous range rate information problem. A smaller and simpler commutator could be made, since the frequency range would be reduced. A display similar to that used for the frequency-definitions analysis (Section 3) would be used.

For a passive sonar system, the Analyzer can be used in its present form with a display such as that shown in Figures 10, 11, and 12. This type of display would show beat notes and frequency shifts of the signal in the water and would prove to be a more quantitative means of identifying various characteristics of signals in the water.

11. CONCLUSIONS

The Audio Spectrum Analyzer MRFR 30-3 is a highly usable instrument for analysis, within the audio spectrum from 40 cps to 4200 cps, of all types of complex waveforms. In conjunction with an oscilloscope using a long persistence screen, the analysis of nonrepetitive waveforms such as underwater sound phenomena associated with active and passive sonar systems can be made to facilitate the identification of audio components present. For active systems information is available, such as target doppler, range rate information, and frequency characteristics of an echo such as may be required for further research into explosive echo-ranging techniques. For passive systems information relative to the frequency components, propeller beats, predominant noise-bands, and audio transients are observable.

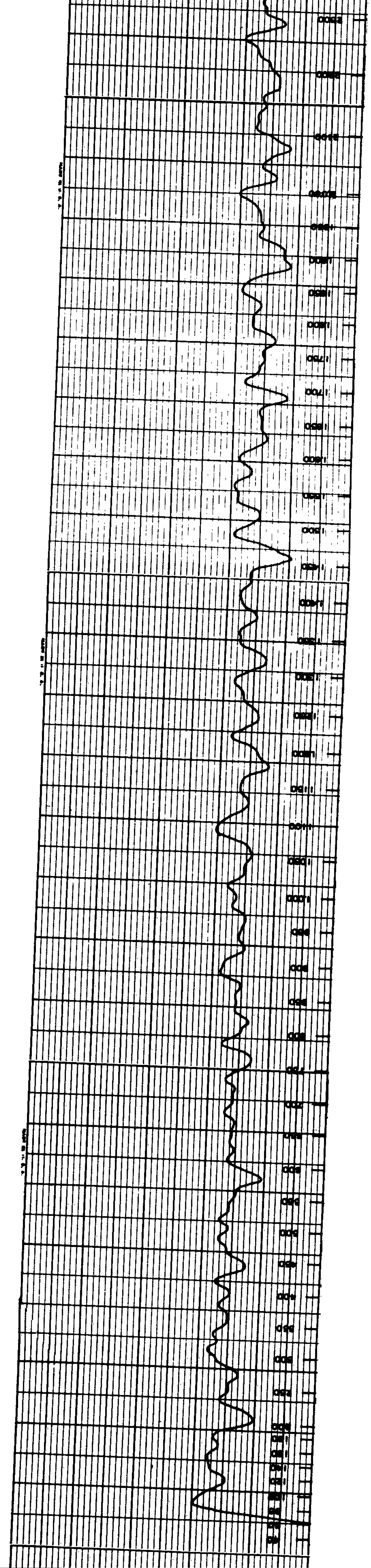
The Analyzer is also useful in the analysis of speech for determining the primary frequency components present in spoken words. Such a system has been built by Raytheon. This could be used in correction of speech difficulties. An advantage of the Analyzer presentation is that the analysis is immediately available as the word is spoken. With the proper photographing process, a permanent record would be obtainable.

12. RESULTS OF RECENT DEVELOPMENT EFFORT

MRFR 30-3, a developmental model Spectrum Analyzer with 10-cycle filters, was completed in November of 1954. Since then several design changes to improve stability and dynamic range have been incorporated. These improvements are the result of an extensive research and development program in progress at the Raytheon laboratories. (The program includes basic metallurgical studies and investigations of heat treatment of various materials, methods of bias and signal application to the rod, and methods and techniques of packaging the filter which lead to greater stability and efficiency.) Also, the electronic circuits associated with the Analyzer have been redesigned to provide a greater linear dynamic range.

Two Spectrum Analyzers which were built recently by Raytheon have a linear dynamic range of approximately 35 db and a frequency response which is within ± 3 db of the average output voltage level (see Figure 22). These Analyzers have filters with an average bandwidth of 32 cycles and cover a 10.5-kc spectrum. Recent development work on very-narrow-band rod filters indicates that comparable analyzers can be built with 5- or 10-cycle filters. A 10-cycle analyzer using the latest techniques currently is being built and should be ready for evaluation early in 1956.

The Missile and Radar Division of the Raytheon Manufacturing Company currently is doing magnetostrictive design work for the development of narrow-band filters under two Air Force-sponsored contracts: (1) Subcontract #2 from Columbia University on their prime contract AF 30(635)-2807; (2) Rome Air Development Center, AF 30(635)-2902.



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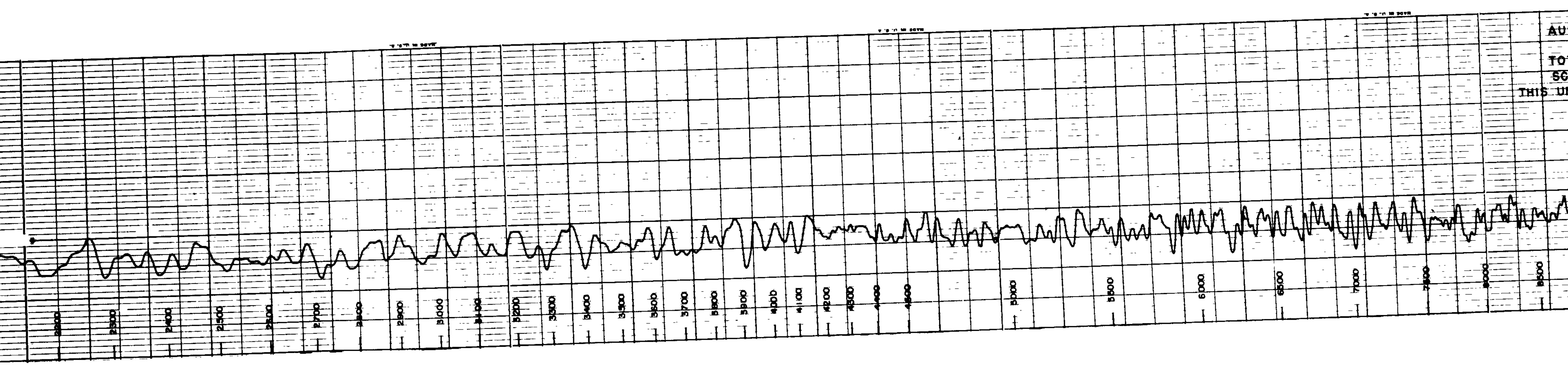

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